DYNAMICAL MESON-BARYON RESONANCES WITH CHIRAL LAGRANGIANS

A. RAMOS, A. PARREÑO
Departament ECM, Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, SPAIN

J.C. NACHER, E. OSET
Departamento de Física Teórica and IFIC, Institutos de Investigación de Paterna, Aptdo. Correos 22085, E-46071 Valencia, SPAIN

C. BENNHOLD
Center for Nuclear Studies, Department of Physics, The George Washington University, Washington D.C. 20052

The s-wave meson-baryon interaction is studied using the lowest-order chiral Lagrangian in a unitary coupled-channels Bethe-Salpeter equation. In the strangeness $S = -1$ sector the low-energy $K^- p$ dynamics leads to the dynamical generation of the $\Lambda(1405)$ as a $\bar{K}N$ state, along with a good description of the $K^- p$ scattering observables. At higher energies, the $\Lambda(1670)$ is also found to be generated dynamically as a $K\Xi$ quasibound state for the first time. For strangeness $S = 0$, it is the $S_{11}(1535)$ resonance that emerges from the coupled-channels equations, leading to a satisfactory description of meson-baryon scattering observables in the energy region around the $S_{11}(1535)$. We speculate on the possible dynamical generation of Ξ resonances within the chiral $S = -2$ sector as $\bar{K}\Lambda$ or $\bar{K}\Sigma$ quasibound states.

1 Introduction

Gaining insight into the nature and properties of baryon resonances is one of the primary goals of hadron physics. In the last years, intensive theoretical and experimental effort has been devoted to clarify the internal structure of many resonances and establish whether they behave as 3-quark objects, as predicted by the constituent quark model, or they can be described mostly in terms of hadronic degrees of freedom, as meson-baryon quasibound states.

In the last decade, chiral perturbation theory (ChPT) has emerged as a powerful scheme that successfully explains not only low-energy meson-meson dynamics[1,2] but also meson-baryon scattering[3,4], provided the interaction is weak as is the case of πN scattering in the strangeness $S = 0$ sector, or $K^+ N$ scattering in the $S = 1$ one. However, the validity of ChPT, which is built as a series expansion in the meson momentum, is limited to *low energies* and, in addition, it is not applicable in the vicinity of *resonances*, which correspond to poles in the T-matrix.

Both difficulties can be overcome within the framework of the chiral Lagrangian, by combining the information contained in it with unitarity using non-perturbative techniques. This has proved to be very successful in both the meson-meson[5,6] and the meson-baryon sector[7,8,9,10]. A review of recent results can be found in Ref. [11].

2 Meson-baryon scattering in coupled channels

Ref. [7] combined the chiral Lagrangian (to lowest and next-to-leading order) and a non-perturbative resummation by solving a coupled-channels Lippmann-Schwinger equation. In the case of $K^- p$ scattering, the channels included were those opened at threshold and, fitting five parameters, the low-energy scattering observables, as well as the properties of the $\Lambda(1405)$ resonance, were well reproduced. A similar procedure was followed in Ref. [8] in terms of the coupled-channels Bethe-Salpeter equation (BSE) given by

$$T_{ij} = V_{ij} + V_{il} G_l T_{lj} \ . \tag{1}$$

It was shown that the data could be well reproduced taking the amplitudes V_{ij} from the lowest order chiral Lagrangian and only one parameter, the cut-off used to regularize the intermediate meson-baryon propagator G_l. The key difference compared to Ref. [7] was the inclusion of all ten possible meson-baryon states constructed from the octet of pseudoscalar mesons and the octet of $1/2^+$ baryons, thus preserving SU(3) symmetry in the limit of equal baryon and meson masses. Another advantage of the lowest-order Lagrangian is that the amplitudes can be factorized on-shell out of the loop integral, thus reducing the coupled-channels problem to a set of coupled algebraic equations.

The unitarization of the chiral amplitudes through the BSE has been shown to be a particular case of the Inverse Amplitude Method when the choice of the regulator allows one to include the second-order chiral contributions by means of only the s-channel loop[5]. Equivalently, the BSE is a particular case of the N/D method when the effects of the unphysical cut (left-hand singularities) are neglected[6].

The amplitudes V_{ij} in Eq. (1) are easily obtained from the lowest order meson-baryon interaction Lagrangian

$$L_1^{(B)} = \langle \bar{B} i \gamma^\mu \frac{1}{4f^2} [(\Phi \partial_\mu \Phi - \partial_\mu \Phi \Phi) B - B (\Phi \partial_\mu \Phi - \partial_\mu \Phi \Phi)] \rangle \ , \tag{2}$$

where Φ and B are the matrices representing the mesons and baryons, respectively. A key ingredient in the BSE is the loop integral, G_l, which in Ref. [8]

reads

$$G_l = i \int \frac{d^4q}{(2\pi)^4} \frac{M_l}{E_l(\vec{q})} \frac{1}{k^0 + p^0 - q^0 - E_l(\vec{q}) + i\epsilon} \frac{1}{q^2 - m_l^2 + i\epsilon}$$
$$= \int_{|\vec{q}|<q_{\rm max}} \frac{d^3q}{(2\pi)^3} \frac{1}{2\omega_l(\vec{q})} \frac{M_l}{E_l(\vec{q})} \frac{1}{\sqrt{s} - \omega_l(\vec{q}) - E_l(\vec{q}) + i\epsilon} , \qquad (3)$$

and has been regularized by means of a cut-off, $q_{\rm max}$. An alternative approach, followed in Ref. [9], is obtained by making use of dimensional regularization

$$G_l = i2M_l \int \frac{d^4q}{(2\pi)^4} \frac{1}{(P-q)^2 - M_l^2 + i\epsilon} \frac{1}{q^2 - m_l^2 + i\epsilon}$$
$$= \frac{2M_l}{16\pi^2} \left\{ a_l(\mu) + \ln \frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s} \ln \frac{m_l^2}{M_l^2} + \right.$$
$$\left. + \frac{\bar{q}_l}{\sqrt{s}} \ln \frac{M_l^2 + m_l^2 - s - 2\sqrt{s}\bar{q}_l}{M_l^2 + m_l^2 - s + 2\sqrt{s}\bar{q}_l} \right\} , \qquad (4)$$

where μ is the regularization scale and $\bar{q}_l$ the on-shell momentum. Obviously, changes in the cut-off value of Eq. (3) can always be accommodated with changes in the regularization scale μ and the corresponding change in the subtraction constant $a_l(\mu)$ in Eq. (4). The dimensional regularization scheme can extend the model to higher energies, while the cut-off method limits the range of applicability to energies whose on-shell momentum $\bar{q}_l$ is smaller than the cut-off value for all channels.

3 Strangeness $S = -1$ sector

We start this section summarizing the findings of Ref. [8] for $\bar{K}N$ scattering. The cut-off method was used with a value for the decay constant of $f = 1.15 f_\pi$ (chosen between $f_\pi = 93$ MeV and $f_K = 1.22 f_\pi$) and a value $q_{\rm max} = 630$ MeV was obtained by reproducing the threshold branching ratios, $\gamma = \Gamma(K^-p \to \pi^+\Sigma^-)/\Gamma(K^-p \to \pi^-\Sigma^+)$, $R_c = \Gamma(K^-p \to \text{charged})/\Gamma(K^-p \to \text{all})$ and $R_n = \Gamma(K^-p \to \pi^0\Lambda)/\Gamma(K^-p \to \text{neutral})$. The above value for f gave the best agreement for the $\Lambda(1405)$ properties seen in the $\pi\Sigma$ mass spectrum, as shown in Fig. 1. In Fig. 2, we show that the low-energy scattering cross sections, not used in the fit, are well reproduced.

In order to assess the range of validity of our approach we explored the region of higher energies, using the dimensional regularization scheme with $\mu = 630$ MeV. In order to maintain the low-energy results, we adjust the subtraction constant a_l to reproduce the value of the loop function G_l at

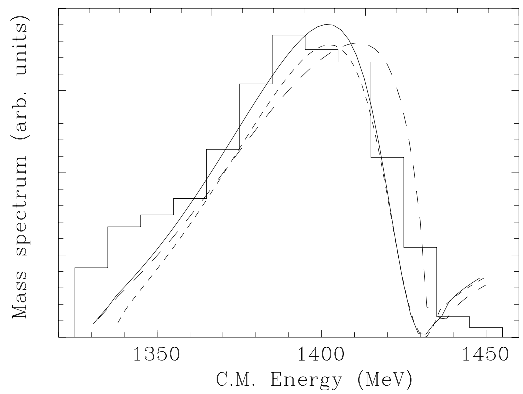


Figure 1. $\Lambda(1405)$ resonance as obtained from the invariant $\pi\Sigma$ mass distribution, with the full basis of physical states (solid line), omitting the η channels (long-dashed line) and with the isospin-basis (short-dashed line). Experimental histogram from Ref. [12]. Figure taken from Ref. [8].

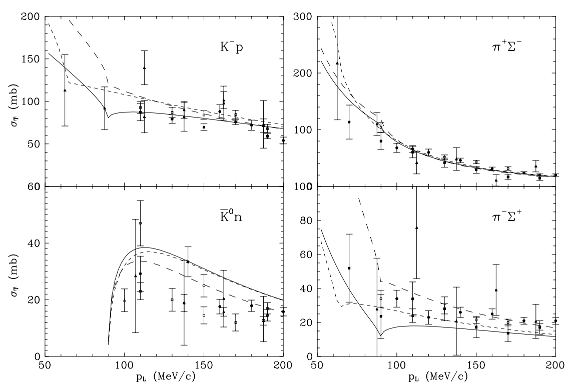


Figure 2. K^-p scattering cross sections as functions of the K^- momentum in the lab frame: with the full basis of physical states (solid line), omitting the η channels (long-dashed line) and with the isospin-basis (short-dashed line). Taken from Ref. [8].

threshold ($\sqrt{s} = m_K + m_N$) calculated with the cut-off, and we find:

$$\begin{array}{lll} a_{\bar{K}N} = -1.84 & a_{\pi\Sigma} = -2.00 & a_{\pi\Lambda} = -1.83 \\ a_{\eta\Lambda} = -2.25 & a_{\eta\Sigma} = -2.38 & a_{K\Xi} = -2.52 \; . \end{array} \tag{5}$$

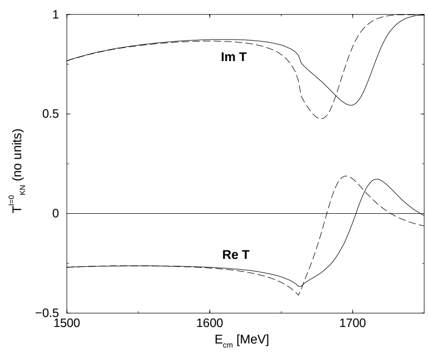


Figure 3. Real and imaginary parts of the $\bar{K}N$ scattering amplitude in the isospin $I = 0$ channel in the region of the $\Lambda(1670)$ resonance.

In Fig. 3, we show the real and imaginary parts of the $I = 0$ scattering amplitude, normalized as in the Partial Wave Analysis of Ref. [13]. Remarkably, the amplitudes shown by the solid lines, which are obtained using the low-energy parameters in Eq. (5), show the resonant structure of the $\Lambda(1670)$ appearing at about the right energy and with a similar size compared to the experimental analysis[13]. The position of the resonance is quite sensitive to the parameter $a_{K\Xi}$ and moderately sensitive to $a_{\eta\Lambda}$. Hence, without spoiling the nice agreement at low energies, which is not sensitive to $a_{K\Xi}$, we exploit the freedom in the parameters by choosing $a_{K\Xi} = -2.70$, moving the resonance closer to its experimental position (dashed lines).

SU(3) symmetry, partly broken here due to the use of physical masses, demands a singlet and an octet of resonances. Within $S = -1$, we have already identified the singlet $\Lambda(1405)$ and the $I = 0$ member of the octet, the $\Lambda(1670)$. Since we found the partial decay widths and couplings[14] of the $\Lambda(1405)$ to $\bar{K}N$ states and the $\Lambda(1670)$ to $K\Xi$ states to be very large, one is naturally led to identify these two resonances as a "quasibound" $\bar{K}N$ and $K\Xi$ state, respectively.

Searching for the $I = 1$ member of the octet, we find that the $I = 1$ amplitudes in our model are smooth and show no trace of resonant behavior, in line with experimental observation. To explore this issue further we conducted a search for the poles of the $\bar{K}N \to \bar{K}N$ amplitudes in the second Riemann sheet and find two poles in the $I = 0$ amplitude $(1426 + i16,\ 1708 + i21)$, corresponding to the $\Lambda(1405)$ and the $\Lambda(1670)$, and one in the $I = 1$ amplitude $(1579 + i296)$, corresponding - most likely - to the resonance $\Sigma(1620)$. The large width found for this resonance may explain why we saw no trace of it in the scattering amplitudes.

4 Strangeness $S = 0$ sector

The success in the s-wave $S = -1$ sector with the lowest-order chiral Lagrangian and only one-parameter[8] encouraged us to study the $S = 0$ sector in the vicinity of the $N(1535)$ resonance. In this case, however, it was not possible to reproduce the elastic πN scattering observables and a few inelastic cross sections with only one parameter. In ref.[15], we adopted a method similar to the dimensional regularization scheme, by using a fixed physical cut-off of 1 GeV, large enough to study the energy region of the $N(1535)$ resonance, and adding a subtraction constant a_l to the loop function G_l. The values of the decay constants were taken different for πN channels ($f_\pi = 93$ MeV), KY channels ($f_K = 1.22 f_\pi$) and ηN channels ($f_\eta = 1.3 f_\pi$). Our $S = 0$ model has then four parameters, $a_{\pi N}$, $a_{\eta N}$, $a_{K\Lambda}$ and $a_{K\Sigma}$, which are fitted to the phase-shifts and inelasticities for πN scattering in isospin $I = 1/2$ around the energy region of the $N(1535)$ resonance, as shown in Fig. 4, and to the inelastic cross section data, as shown in Fig. 5. The analysis performed in Ref. [15] leads to a dynamical generation of the $N(1535)$ state with a total decay width of $\Gamma \simeq 110$ MeV, divided between $\Gamma_\pi \simeq 43$ MeV and $\Gamma_\eta \simeq 67$ MeV, compatible with present data within errors. This simplified model allows one to tackle other issues, such as the evaluation of the $\pi^0 N^* N^*$ and $\eta N^* N^*$ couplings, which elucidates the question of whether the positive parity N and the negative parity N^* are chiral partners when chiral symmetry is restored[15].

We note that a recent work, which also uses the chiral Lagrangian together with a Bethe-Salpeter unitarization scheme, achieves a satisfactory description of the $S = 0$ s-wave observables in the $I = 1/2$ sector from πN threshold up to 2 GeV (similar in quality to our $S = -1$ description) by fitting 12 parameters[10], generating the both the $N(1535)$ and $N(1650)$ S_{11} resonances in the process.

5 Strangeness $S = -2$ sector

Within SU(3) the chiral meson-baryon Lagrangian naturally extends to the $S = -2$ sector. Thus, the dynamics of the $\bar{K}\Lambda$ or $\pi\Xi$ interaction can be predicted within the same approach. Due to the experimental difficulties there are very few scattering data on such reactions. Furthermore, little is known about Ξ resonances since they can only be produced as part of a multiparticle final state with small production cross sections. Nevertheless,

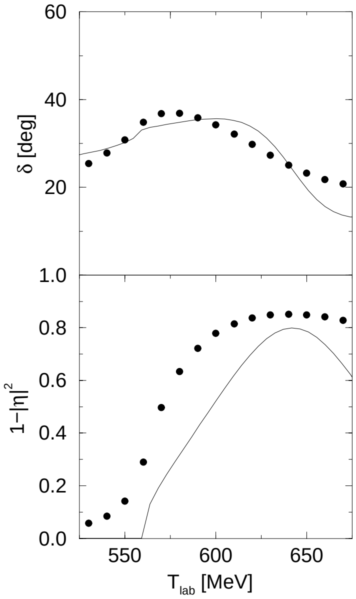


Figure 4. Phase-shifts and inelasticities for πN scattering in the isospin $I = 1/2$ channel. Taken from Ref. [15].

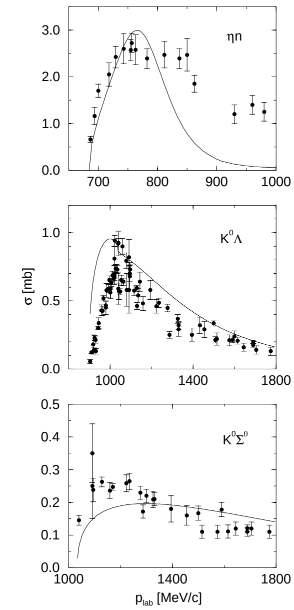


Figure 5. Cross sections for the $\pi^- p \to \eta n$, $K^0\Lambda$ and $K^0\Sigma^0$ reactions as function of the π^- laboratory momentum. Taken from Ref. [15].

given the success of the approach presented here in generating most of the $(70, 1_1^-)$ octet of $1/2^-$ excited baryon states in the $S = 0$ and $S = -1$ sector, it is reasonable to assume that its missing member in the $S = -2$ realm, a Ξ^* resonance, will be produced as well. Among the observed states, two "suspects" stand out: the $\Xi(1620)$ and the $\Xi(1690)$, with unknown spin and parity. The $\Xi(1690)$ might be the more plausible candidate since it has strong couplings to the $\bar{K}\Lambda(\Sigma)$ channels which may serve as identifying features.

6 Conclusions

We have extended the previously reported $S = -1$ meson-baryon scattering approach[8] to higher energies of up to 2 GeV. This study has revealed the appearance of two other resonances, the $\Lambda(1670)$ and the $\Sigma(1620)$, both belonging to the octet, dynamically generated as $K\Xi$ states.

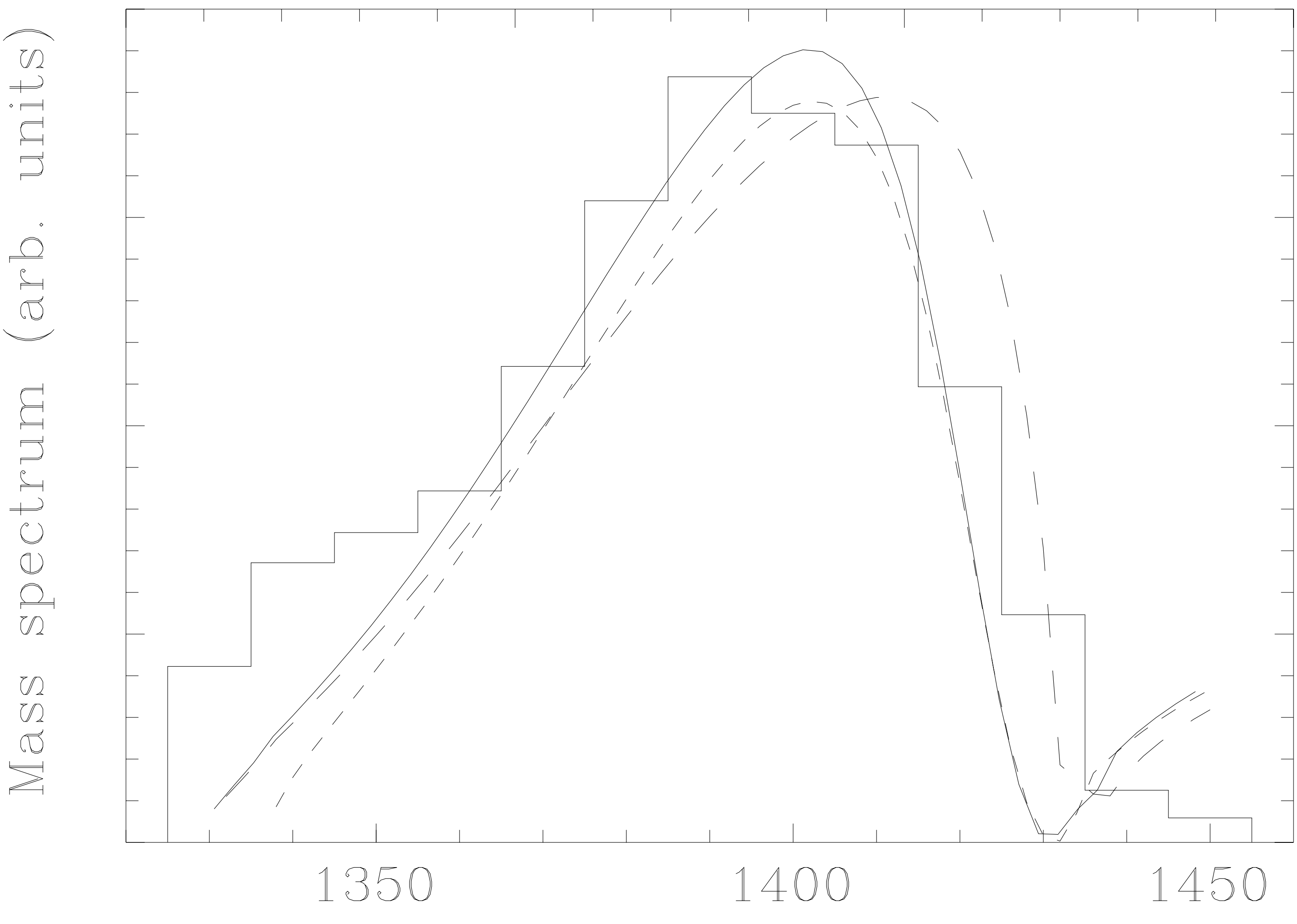
The $S = 0$ sector has been more difficult to describe with only a few parameters, although the model presented here is able to reproduce the πN data moderately well around the energy of the $N(1535)$ and allows one to tackle other issues related to the $N(1535)$, such as its couplings to π and η mesons[15]. A complete description from low to high energies, as presented here for the $S = -1$ sector, has not been possible within our simple approach, but it has been achieved in the $I = 1/2$ sector using an extended parameter set[10]. Given the success of this method of producing the members of the $1/2^-$ octet of excited states in the $S = 0$ and $S = -1$ sectors, it is reasonable to assume that an extension to the $S = -2$ realm will generate the missing octet member, a Ξ resonance in the energy region of 1600-1700 MeV. Confirmation of such a state would further demonstrate the power of combining the chiral meson-baryon Lagrangian with non-perturbative unitarization techniques.

Acknowledgments

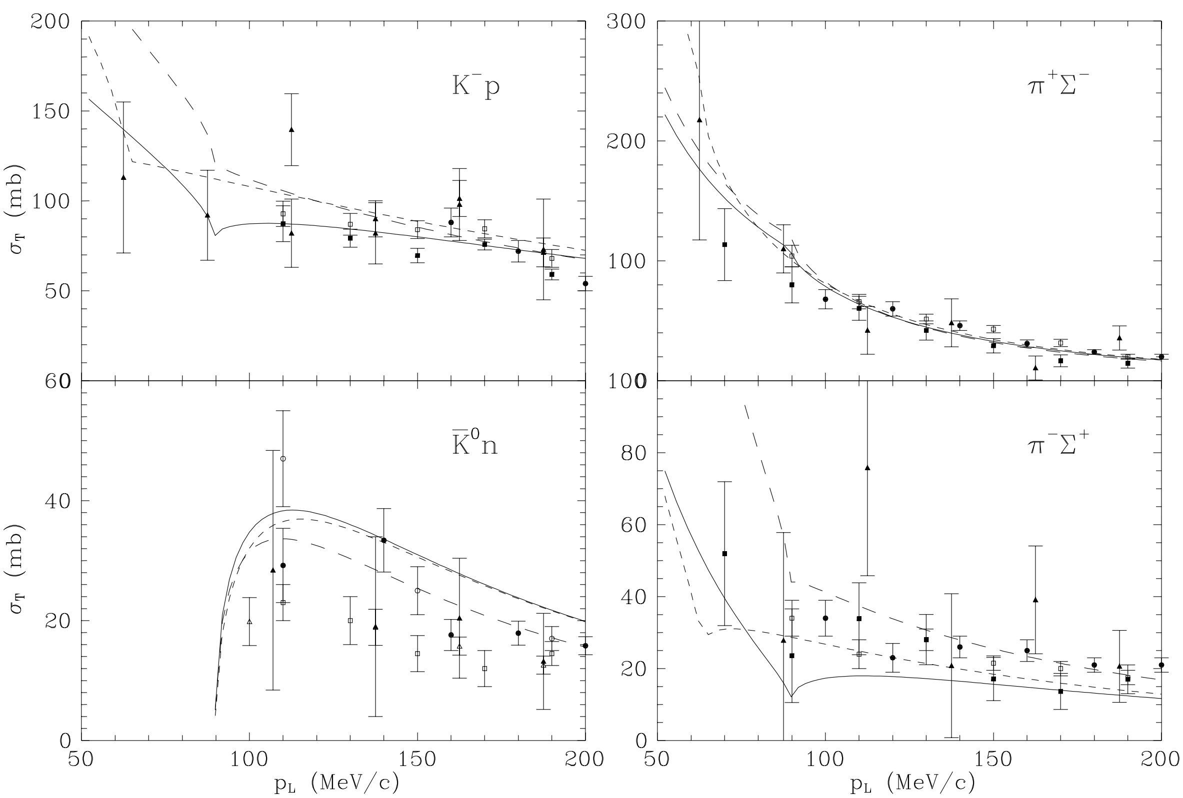
This work has been supported by DGICYT contract numbers BFM2000-1326, PB98-1247, by the Generalitat de Catalunya project SGR2000-24, by the EU TMR network Eurodaphne, contract no. ERBFMRX-CT98-0169, and by US-DOE grant DE-FG02-95ER-40907.

References

1. J. Gasser and H. Leutwyler, Nucl. Phys. B250 (1985) 465
2. A. Pich, Rep. Prog. Phys. 58 (1995) 563
3. G. Ecker, Prog. Part. Nucl. Phys. 35 (1995) 1
4. V. Bernard, N.Kaiser, U.G. Meissner, Int. J. Mod. Phys. E4 (1995) 193
5. J. A. Oller, E. Oset, and J. R. Peláez, Phys. Rev. Lett. 80 (1998) 3452; Phys. Rev. D 59 (1999) 074001; erratum Phys. Rev. D 60 (1999) 099906
6. J.A. Oller and E. Oset, Phys. Rev. D60 (1999) 074023
7. N. Kaiser, P. B. Siegel and W. Weise, Nucl. Phys. A594 (1995) 325; N. Kaiser, T. Waas and W. Weise, Nucl. Phys. A612 (1997) 297
8. E. Oset and A. Ramos, Nucl. Phys. A635 (1998) 99
9. J.A. Oller and U.G. Meissner, Phys. Lett. B500 (2001) 263
10. J. Nieves and E. Ruiz Arriola, hep-ph/0104307
11. J.A. Oller, E. Oset, A. Ramos, Prog. Part. Nucl. Phys. 45 (2000) 157
12. R.J. Hemingway, Nucl. Phys. B253 (1985) 742
13. G.P. Gopal et al., Nucl. Phys. B119 (1977) 362
14. E. Oset, A. Ramos and C. Bennhold, in preparation
15. J.C. Nacher, A. Parreño, E. Oset, A. Ramos, A. Hosaka and M. Oka, Nucl. Phys. A678 (2000) 187



Mass spectrum (arb. units)
1350
1400
1450
C.M. Energy (MeV)



K^-p
$\pi^+\Sigma^-$
$\bar{K}^0n$
$\pi^-\Sigma^+$
σ_T (mb)
p_L (MeV/c)